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ENERGY EFFICIENCY OF HEAT PUMPING STATIONS WITH DIFFERENT HEAT SOURCES ON CONDITION OF VARIABLE OPERATION MODES

The paper determines modes of efficient operation of heat pumping stations (HPS) with different types of compressor drive and sources of low-temperature heat on condition of variable operation modes of heat supply systems. The suggested recommendations make it possible to choose HPS and low-temperature sources operation modes in order to achieve the desired values of efficiency indices for HPS year-round operation. The suggested recommendations can be used for the forecast of rational operation modes of HPS of various capacity in heat supply systems.

Key words: *energy efficiency, heat pumping station, heat pumping, installation, operation mode of heat supply systems.*

Introduction

Shortage of fuel and energy resources in Ukraine and environmental advantages of heat pumps stimulate introduction of heat pumping stations (HPS) into industry and municipal power supply systems. Construction of heat pumping stations on the basis of boiler houses will make it possible to reduce natural gas consumption and the cost of thermal power. All this stipulates the urgency of the resources, devoted to the study of energy efficiency of heat pump stations.

In recent years a number of research, aimed at investigation of heat pumping stations (HPS), operation efficiency in thermal networks of energy supply sources have been conducted. In [1] the authors have performed research, aimed at improving energy efficiency of energy supply sources using heat pumping stations (HPS), taking into account the impact of circuit solutions and operation modes. In research [2] “the efficiency function” of HPS, presented by fuel saving in energy supply system evaluating energy efficiency and increment of integral effect. In [3] the combined schemes of heat supply from HPS using low temperature heat from various sources at industrial power plants are considered. In research [4] the efficiency of HPS with electric drive and gas-turbine drive and waste-heat boiler has been analyzed.

Authors in [5] have performed comparative investigations of three energy supply systems based on gas-fired boiler and cogeneration unit with heat pump. In [6] the evaluation of the efficiency of four sources of energy supply, rated for 3 MW, based on electric boiler, fuel boiler (gas, liquid fuel) and heat-pumping unit has been carried out. In [7] the evaluation of energy efficiency of heat pumping unit of small power compared with conventional sources of heat supply, based on electric and gas-fired boiler was performed.

In research [1 – 7] evaluation of heat-pumping stations efficiency was performed according to such criteria: transformation factor, saving of working and conventional fuel in comparison with the existing scheme, by economic indices.

In research analyzed [1 – 7], the authors did not perform the evaluation of energy efficiency of HPP with various types of drive with variable operation modes of heat supply systems in a wide range of HPS power. Analysis of HPP energy efficiency with various sources of low temperature heat is missing.

The aim of the research is evaluation of the efficiency of HPS with different types of the compressor drive at various sources of low temperature heat, taking into account variable operation modes of heat supply systems in wide range of HPS power change; realization of optimization research in order to determine rational operation modes of HPP of various power in heat supply systems.

Main part

Research has been carried out, applying the method of mathematical modeling of HPS operation using the program in Excel environment. The program is used for modeling of heat pumping stations with various types of compressor drive for heat supply. The program is of block structure and consists of such computational modules: calculation of heating scheme of water heating boiler, calculation heat pumping unit, calculation of internal combustion engine and system of heat utilization, calculation of energy efficiency of heat pumping station. Module selection of the source of low temperature heat for HPS and its temperature level depending on HPS operation mode is provided.

Energy efficiency of HPS with electric drive and compressor drive from internal combustion engine (ICE) of maximum power of 10 MW in heating period was studied maximum power of HPS in operation mode of hot water supply was 2 MW. As the comparison variant, the variant of hot-water boiling house of the same capacity was taken. The study was carried out for various sources of low temperature heat, taking into account variable operation modes of HPS for heat supply systems in wide range of heat pump power change. Power of heat pump condenser changed from 500 to 2000 KW in accordance with the types of heat pumping equipment, produced by manufactures [8]. Sources of low temperature heat for HPS were: surface waters, circulating water supply, soil waters, geothermal waters, air, secondary energy resources (SER), sewage and heat of the ground.

Efficiency of HPS operation is greatly determined by optimal distribution of load among heat pumping station and hot water boiler in HPS. Distribution of load among the elements of HPS is characterized by the portion of HPU in HPS β, which is determined as the relation HPU condenser capacity to the power of HPS.

$$\beta = \frac{Q_{HPU}}{Q_{HPS}}. \tag{1}$$

Power and temperature modes of heat pumping station operation in heat supply system are defined by the temperature graph, depending on the temperature of ambient air and necessary power of loads.

On the basic of the analysis of the results obtained, optimal values of β index for HPS operating on various sources of heat with different types of HPU compressor drive on condition of variable operation mode of heat supply network, are determined. Certain value of thermal capacities of HPS, HPU and portion of HPU β load portion corresponds to each of these modes.

For the cases of variable operation modes and variable heat loading of HPS during the year, average annual value of portion of HPU load can be determined:

$$\beta_{aver.an} = \frac{\sum_i \beta_i \cdot \tau_i}{\tau_{an}}, \tag{2}$$

where β_i – is the portion of HPU loading for i^{th} mode of HPS operation; τ_i – is the duration of i^{th} operation mode of HPS; τ_{an} – is annual duration of HPS operation.

Saving of equivalent fuel as a result of HPS introduction is considerably determined by optimally selected operation modes of HPS, rational distribution of loading between hot water boiler and HPU, thus – by optimal value of the portion of HPU loading within HPS β. On the basis of the determined values of HPU β loading portion, saving of the equivalent fuel of HPS is defined for certain mode of heat supply system operation.

For the cases of variable operation modes and variable heat loading of HPS during a year, average annual value of equivalent fuel saving for HPS can be determined as:

$$\Delta B_{aver.an} = \frac{\sum_i \Delta B_i \cdot \tau_i}{\tau_{an}}, \tag{3}$$

where ΔB_i – is saving of equivalent fuel as a result of HPS introduction for i^{th} mode of HPS operation, %; τ_i – is the duration of i^{th} mode of HPS operation; τ_{an} – is annual duration of HPS operation.

The suggested criteria allow to evaluate energy efficiency of HPS operation during a year at various operation modes.

Table 1

Indices of energy efficiency of HPS operation on the heat of surface waters and circulating water

Power of HPU, KW		Saving of equivalent fuel of HPS with electric drive, %		Saving of equivalent fuel of HPS with the drive from internal combustion engine (ICE), %		Average annual saving of equivalent fuel of HPS with electric drive, %	Average annual saving of equivalent fuel of HPS with the drive from ICE, %	Portion of thermal capacity, covering β of HPU		
Heating season	Interheating period	Heating season	Interheating period	Heating season	Interheating period			Heating season	Interheating period	Average value per year
Indices of energy efficiency of HPS operating on the heat of surface waters										
500	500	-22.92	4.73	1.84	11.32	-8.69	6.66	0.0609	0.25	0.158
1000	500	-14.98	4.73	5.94	11.32	-4.84	8.64	0.121	0.25	0.187
1500	500	-7.04	4.73	10.57	11.32	-0.99	10.88	0.182	0.25	0.2165
2000	500	0.901	4.73	15.81	11.32	2.86	13.41	0.243	0.25	0.246
1000	1000	-14.98	9.46	5.94	24.35	-2.42	15.3	0.121	0.5	0.315
1500	1000	-7.04	9.46	10.57	24.35	1.43	17.53	0.182	0.5	0.344
2000	1000	0.901	9.46	15.81	24.35	5.27	20.06	0.243	0.5	0.374
1500	1500	-7.04	14.19	10.57	39.88	3.95	25.45	0.182	0.75	0.472
2000	1500	0.901	14.19	15.81	39.88	7.7	27.98	0.243	0.75	0.502
2000	2000	0.901	18.92	15.81	59.26	10.12	37.87	0.243	1	0.629
Indices of energy efficiency of HPS operating on the heat of circulating water										
500	500	-14.61	10.51	3.06	15.15	-1.7	9.21	0.0609	0.25	0.158
1000	500	-6.67	10.51	8.25	15.15	2.15	11.72	0.121	0.25	0.187
1500	500	1.27	10.51	13.06	15.15	6.00	14.40	0.182	0.25	0.2165
2000	500	9.21	10.51	19.79	15.15	9.85	17.29	0.243	0.25	0.246
1000	1000	-6.67	21.03	8.25	31.52	7.53	20.07	0.121	0.5	0.315
1500	1000	1.27	21.03	13.06	31.52	11.38	22.85	0.182	0.5	0.344
2000	1000	9.21	21.03	19.79	31.52	15.23	25.64	0.243	0.5	0.374
1500	1500	1.27	31.54	13.06	49.65	16.76	31.99	0.182	0.75	0.472
2000	1500	9.21	31.54	19.79	49.65	20.61	34.88	0.243	0.75	0.502
2000	2000	9.21	42.05	19.79	70.48	26.00	45.52	0.243	1	0.629

The results of the study of HPS operation efficiency on various sources of heat and with different types of drive on condition of variable operation modes of HPS, are given in Tables, presented below. The Tables contain power of HPU, values of HPU loading portions. Values of equivalent fuel saving by HPS with electric drive and drive from ICE are indicated for heating and interheating modes and also average annual values of these indices depending on the portion of HPU loading.

Table 1 contains values of energy efficiency indices of HPS operation on the heat of surface waters and circulating water, with electric drive and compressor drive from ICE on condition of variable operation modes of HPS. As it is seen from Table 1, the greatest values of HPS - equivalent fuel saving correspond to maximal values of HPU loading portion. For HPS with electric drive, operating on the heat of surface waters, saving of equivalent fuel is provided not only for all modes of HPS operation, considerable saving of equivalent fuel is provided for operation modes of HPS with average annual value of HPU loading portion β>0.502. Maximum value of annual saving of equivalent fuel by HPS with electric drive, operating of the heat of surface waters is 10,12% and corresponds to average annual value of HPU loading portion β=0.629. For HPS with the drive from ICE, operating on the heat of surface waters, maximum values of annual saving of equivalent fuel is 37.87% and corresponds to average annual value of HPU loading portion β=0.629.

Table 1 also contains values of energy efficiency indices of HPS, operating on the heat of circulating water with electric drive and compressor drive from ICE on condition of variable operation modes of HPS. For such HPS with electric drive, saving of equivalent fuel is provided for HPS operation modes with average annual value of loading portion of HPU β>0.187. As in the previous case, the greatest values of saving of HPS equivalent fuel correspond to maximum values of HPU loading portion. Maximum values of annual saving of equivalent fuel for HPS, operating on the heat of circulating water are: for electric drive – 26%, for the drive from ICE – 45.52% and correspond to average annual value of loading portion of HPU β=0.629.

Values of energy efficiency indices of HPS, operating on ground and geothermal waters, with various types of drive, on condition of variable operation modes of HPS, are shown in Table 2.

As it is seen from Table 2, the greatest values of equivalent fuel saving for HPS correspond to maximum values of HPU loading portion. For HPS with electric drive the saving of equivalent fuel is provided for HPS operation modes with average annual value of HPU loading portion β>0.502. Maximum values of equivalent fuel annual saving for HPS, operating on the heat of ground waters are: for electric drive – 5.64%, for the drive from ICE – 35.07% and correspond to average annual value of HPU loading portion β=0.629.

Table 2 contains efficiency indices of HPS with different drives operating of the heat of geothermal water, under condition of variable operation modes of HPS depending on the portion of HPU loading. Saving of equivalent fuel is provided for all operation modes of HPS. Maximum values of equivalent fuel saving of such HPS correspond to maximum values of the portion of HPU load. Maximum values of annual saving of equivalent fuel for HPS operating on the heat of geothermal water are: for electric drive – 44.49%, for the drive from ICE – 54.255% and correspond to annual value of HPS load portion β=0.629.

Values of the efficiency of HPS operating on the heat of air with different types of drive, at different modes of HPS operation are shown in Table 3. For HPS with electric drive overexpenditure of equivalent fuel is shown for HPS operation modes with average annual of HPS load portion of β<0.502. This shows that operation of HPS with such source of heat and type of drive is not efficient for all operation modes. For HPS with the drive of ICE the saving of equivalent fuel for all operation modes is observed, the greatest value of annual saving of HPS fuel is 31.16% and corresponds to average annual value of HPS load portion β=0.629.

Table 2

Indices of energy efficiency of HPS operation on the heat of ground and geothermal waters

Power of HPU, KW		Saving of equivalent fuel of HPS with electric drive, %		Saving of equivalent fuel of HPS with the drive from internal combustion engine (ICE), %		Average annual saving of equivalent fuel of HPS with electric drive, %	Average annual saving of equivalent fuel of HPS with the drive from ICE, %	Portion of thermal capacity, covering *β* of HPU		
Heating season	Interheating period	Heating season	Interheating period	Heating season	Interheating period			Heating season	Interheating period	Average value per year
Indices of energy efficiency of HPS operating on the heat of ground waters										
500	500	-22.92	2.54	1.84	9.86	-9.8	5.92	0.0609	0.25	0.158
1000	500	-14.98	2.54	5.94	9.86	-5.95	7.91	0.121	0.25	0.187
1500	500	-7.04	2.54	10.57	9.86	-2.11	10.14	0.182	0.25	0.2165
2000	500	0.901	2.54	15.81	9.86	1.74	12.67	0.243	0.25	0.246
1000	1000	-14.98	5.09	5.94	21.64	-4.67	13.91	0.121	0.5	0.315
1500	1000	-7.04	5.09	10.57	21.64	-0.8	16.14	0.182	0.5	0.344
2000	1000	0.901	5.09	15.81	21.64	3.04	18.67	0.243	0.5	0.374
1500	1500	-7.04	7.63	10.57	36.18	0.49	23.57	0.182	0.75	0.472
2000	1500	0.901	7.63	15.81	36.18	4.34	26.09	0.243	0.75	0.502
2000	2000	0.901	10.17	15.81	55.02	5.64	35.07	0.243	1	0.629
Indices of energy efficiency of HPS operating on the heat of geothermal waters										
500	500	0.44	16.13	5.28	29.13	6.98	17.205	0.0609	0.25	0.158
1000	500	8.38	16.13	12.46	29.13	12.31	20.795	0.121	0.25	0.187
1500	500	16.32	16.13	19.73	29.13	16.17	24.43	0.182	0.25	0.2165
2000	500	24.26	16.13	27.13	29.13	20.02	28.13	0.243	0.25	0.246
1000	1000	8.38	32.26	12.46	38.49	20.57	25.475	0.121	0.5	0.315
1500	1000	16.32	32.26	19.73	38.49	24.42	29.11	0.182	0.5	0.344
2000	1000	24.26	32.26	27.13	38.49	28.27	32.81	0.243	0.5	0.374
1500	1500	16.32	48.39	19.73	59.12	32.68	39.425	0.182	0.75	0.472
2000	1500	24.26	48.39	27.13	59.12	36.53	43.125	0.243	0.75	0.502
2000	2000	24.26	64.52	27.13	81.38	44.49	54.255	0.243	1	0.629

Table 3 also contains values of efficiency indices, for HPS operating on the heat of secondary energy resources with different types of the drive, depending on the portion of HPU loading. For HPS with electric drive considerable saving of equivalent fuel is provided for HPS operation modes with average annual value of HPU loading portion β>0.374. The greatest values of equivalent fuel saving of such HPS correspond to maximum values of HPU loading portion. Maximum values of annual fuel saving of HPS, operating on the heat of secondary energy resources are: for electric drive – 57.84%, for the drive from ICE – 60.93% and corresponds to average annual value of HPU loading portion β=0.629.

Table 3

Indices of energy efficiency of HPS operation on the heat of the air and SER

Power of HPU, KW		Saving of equivalent fuel of HPS with electric drive, %		Saving of equivalent fuel of HPS with the drive from internal combustion engine (ICE), %		Average annual saving of equivalent fuel of HPS with electric drive, %	Average annual saving of equivalent fuel of HPS with the drive from ICE, %	Portion of thermal capacity, covering β of HPU		
Heating season	Interheating period	Heating season	Interheating period	Heating season	Interheating period			Heating season	Interheating period	Average value per year
Indices of energy efficiency of HPS operating on the heat of the air										
500	500	-26.47	2.54	1.32	9.87	-11.53	5.67	0.0609	0.25	0.158
1000	500	-18.53	2.54	4.97	9.87	-7.68	7.43	0.121	0.25	0.187
1500	500	-10.59	2.54	9.2	9.87	-3.83	9.47	0.182	0.25	0.2165
2000	500	-2.65	2.54	14.12	9.87	0.016	11.86	0.243	0.25	0.246
1000	1000	-18.53	5.08	4.97	21.64	-6.38	13.43	0.121	0.5	0.315
1500	1000	-10.59	5.08	9.2	21.64	-2.53	15.48	0.182	0.5	0.344
2000	1000	-2.65	5.08	14.12	21.64	1.31	17.86	0.243	0.5	0.374
1500	1500	-10.59	7.63	9.2	38.8	-1.23	22.9	0.182	0.75	0.472
2000	1500	-2.65	7.63	14.12	38.8	2.62	25.28	0.243	0.75	0.502
2000	2000	-2.65	10.17	14.12	55.02	3.92	34.89	0.243	1	0.629
Indices of energy efficiency of HPS operating on the heat of SER										
500	500	2.57	22.07	5.53	22.83	12.39	14.32	0.0609	0.25	0.158
1000	500	10.2	22.07	12.97	22.83	16.52	17.91	0.121	0.25	0.187
1500	500	18.14	22.07	20.46	22.83	20.09	21.53	0.182	0.25	0.2165
2000	500	26.08	22.07	28.03	22.83	23.93	25.18	0.243	0.25	0.246
1000	1000	10.2	44.14	12.97	45.85	27.54	29.66	0.121	0.5	0.315
1500	1000	18.14	44.14	20.46	45.85	31.4	33.27	0.182	0.5	0.344
2000	1000	26.08	44.14	28.03	45.85	35.24	36.93	0.243	0.5	0.374
1500	1500	18.14	66.22	20.46	69.16	42.69	45.16	0.182	0.75	0.472
2000	1500	26.08	66.22	28.03	69.16	46.54	48.82	0.243	0.75	0.502
2000	2000	26.08	88.29	28.03	92.91	57.84	60.93	0.243	1	0.629

Values of the efficiency of HPS operating on the heat of sewage with different types of drive, at variable modes of HPS operation are shown in Table 3. For such HPS with electric drive considerable saving of equivalent fuel is provided for HPS operation modes with average annual of HPU load portion β>0.374. As in previous cases, the greatest values of HPS equivalent fuel saving correspond to maximum values of HPU load portion. Maximum values of annual saving of HPS equivalent fuel, operating on the heat of sewage are: electric drive—10.41%, for the drive from ICE---38%, and correspond to average annual value of HPU load portion β=0.629.

Table 4

Indices of energy efficiency of HPS operation on the heat of the sewage and ground

Power of HPU, KW		Saving of equivalent fuel of HPS with electric drive, %		Saving of equivalent fuel of HPS with the drive from internal combustion engine (ICE), %		Average annual saving of equivalent fuel of HPS with electric drive, %	Average annual saving of equivalent fuel of HPS with the drive from ICE , %	Portion of thermal capacity, covering β of HPU		
Heating season	Interheating period	Heating season	Interheating period	Heating season	Interheating period			Heating season	Interheating period	Average value per year
Indices of energy efficiency of HPS operating on the heat of sewage										
500	500	-22.32	4.73	1.93	11.32	-8.39	6.71	0.0609	0.25	0.158
1000	500	-14.37	4.73	6.11	11.32	-4.55	8.73	0.121	0.25	0.187
1500	500	-6.43	4.73	10.80	11.32	-0.69	10.99	0.182	0.25	0.2165
2000	500	1.51	4.73	16.10	11.32	3.15	13.55	0.243	0.25	0.246
1000	1000	-14.37	9.46	6.11	24.35	-2.12	15.38	0.121	0.5	0.315
1500	1000	-6.43	9.46	10.80	24.35	1.72	17.64	0.182	0.5	0.344
2000	1000	1.51	9.46	16.10	24.35	5.57	20.2	0.243	0.5	0.374
1500	1500	-6.43	14.19	10.80	39.88	4.19	25.56	0.182	0.75	0.472
2000	1500	1.51	14.19	16.10	39.88	8.00	28.12	0.243	0.75	0.502
2000	2000	1.51	18.91	16.10	59.26	10.41	38.00	0.243	1	0.629
Indices of energy efficiency of HPS operating on the heat of the ground										
500	500	-31.36	0.39	0.61	8.44	-14.99	4.06	0.0609	0.25	0.158
1000	500	-23.42	0.39	3.62	8.44	-11.15	6.06	0.121	0.25	0.187
1500	500	-15.48	0.39	7.32	8.44	-7.29	7.84	0.182	0.25	0.2165
2000	500	-7.53	0.39	11.82	8.44	-3.44	10.02	0.243	0.25	0.246
1000	1000	-23.42	0.79	3.62	18.97	-10.94	11.43	0.121	0.5	0.315
1500	1000	-15.48	0.79	7.32	18.97	-7.09	13.22	0.182	0.5	0.344
2000	1000	-7.53	0.79	11.82	18.97	-3.24	15.39	0.243	0.5	0.374
1500	1500	-15.48	1.19	7.32	32.56	-6.89	20.14	0.182	0.75	0.472
2000	1500	-7.53	1.19	11.82	32.56	-3.06	22.32	0.243	0.75	0.502

2000	2000	-7.53	1.59	11.82	50.85	-2.84	31.16	0.243	1	0.629

Table 4 contains values of efficiency indices for HPS operating on the heat of the soil with different types of the drive, depending on the portion of HPU loading. For such HPS with electric drive excessive overexpenditure of equivalent fuel for greater part of HPS operation modes is observed. Operation of HPS with such source of heat and type of the drive is inefficient. For HPS operating on the heat of soil with the drive from ICE saving of equivalent fuel for all operation modes is observed, the greatest value of annual saving of equivalent fuel for HPS is 31.16% and corresponds to average annual value of HPU loading portion β=0.629.

Rational operation modes of HPS of various capacity in heat supply systems in wide range of HPS power change were determined and substantiated, taking into account complex impact of low temperature heat sources and type of HPU compressor drive.

The presented results of investigations allow to evaluate energy efficiency of HPS with different types of compressor drive and sources of low temperature heat on condition of variable operation modes of heat supply systems. The suggested recommendations enable to select HPS operation modes and sources of low temperature heat to achieve the preset values of HPS operation efficiency indices.

These recommendations can be used to forecast rational operation modes of HPS of various capacity in heat supply systems.

Conclusions

1. Considerable saving of equivalent fuel as a result application of electrically driven HPS is provided for operation modes with considerable portions of loading of HPS heat pump β>0.502. Maximum values of annual saving of electrically-driven HPS equivalent fuel are observed for such sources of low temperature heat as: secondary energy resources – 57.84%, geothermal water – 44.49%, circulating water – 26.00%, sewage – 10.41%. Operation modes of electrically-driven HPS with average annual value of HPU loading portion β<0.502, operating on the heat of the air is inefficient due to excessive consumption of equivalent fuel. Operation of electrically-driven HPS on the heat of the soil is inefficient because excessive consumption of equivalent fuel is registered for greater part of operation modes.

2. If HPS with the drive from ICE is used saving of equivalent fuel is observed for all studied sources of low temperature heat and operation modes. The greatest values of annual saving of fuel of such HPS correspond to average annual value of heat pump loading portion β=0.629. Maximal values of annual saving of equivalent fuel for HPS with the drive from ICE are observed for such sources of low temperature heat: secondary energy resources – 60.93%, geothermal water – 54.26%, circulating water – 45.25%, sewage – 38%. Minimal value of annual saving of equivalent fuel for HPS with the drive from ICE is provided when the heat of ground waters is 5.64%.

3. Modes of efficient operation of HPS with various types of compressor drive and sources of low temperature heat on conditions of variable operation modes of heat supply systems are determined and substantiated. The suggested recommendations allow to perform the choice of HPS operation modes and sources of low temperature heat in order to achieve the preset values of efficiency indices of HPS annual operation. These recommendations can be used for the forecast of rational modes of HPS of different power operation in heat supply systems.

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